Dean&Francis
ISSN 2959-6157

Research Progress on the Application of Graphene in Cable Materials

Yu Li[1, *]

[1]School of Electrical and Electronic Engineering, Harbin University of Science and Technology, Harbin, China

*Corresponding author: 2103010309@stu.hrbust.edu.cn

Abstract:

Cable materials encompass a diverse array of components, including metal conductors, semi-conductive shielding materials, the preferred insulating elements of cables, and cable accessory insulation materials, in addition to other related components. The performance of cable conductor materials has a direct impact on the amount of current that can be carried and the transmission loss. Consequently, the development of high-conductivity cable conductor materials represents the current primary research focus of the cable industry. Given its exemplary conductivity and substantial mechanical strength, graphene represents a pivotal material for enhancing the conductive attributes of copper conductors. Moreover, conventional cable semiconducting shielding materials are typically enhanced in conductivity through the incorporation of carbon black. Similarly, graphene has the potential to serve as a viable alternative for improving the conductivity characteristics of semiconducting shielding materials. This paper presents a study of the application of graphene in cable materials, with a particular focus on its role in enhancing the conductive properties of copper cable conductors and semiconducting shielding materials. This thesis begins with a comprehensive examination of graphene's electrical and mechanical properties, emphasizing its remarkable performance. It then explores the use of graphene in cable materials and the potential applications for graphene cables. The objective of this paper is to serve as a reference point for the advancement of high-performance cable materials based on graphene research.

Keywords: Cable materials; cable conductor materials; graphene; semi-conductive shielding; graphene cable.

ISSN 2959-6157

1. Introduction

The wire and cable industry plays a pivotal role in the broader economic landscape, serving as a crucial supporting sector for the two foundational economic industries of electricity and communication. Its products are instrumental in the transmission of power and the transfer of information, underscoring the vital function they perform in modern society. In recent years, China's wire and cable industry has undergone a period of rapid development, becoming the world's largest manufacturer and consumer of wire and cable products. While the scale of China's wire and cable industry is among the world's leading, it is still smaller in comparison to Europe, America, Japan, and other developed countries, there is a high degree of product homogenization, with low-end conventional wire and cable products representing the majority of the market. The industry is characterized by intense competition and a low degree of concentration, with technology convergence playing a significant role in shaping the competitive landscape[1][2].

Concurrently, the modern electrical fields, such as those utilized in aerospace equipment and high-power transmission equipment, have resulted in increasingly demanding wire and cable performance requirements. The traditional wire and cable conductor materials, namely copper and aluminum, have reached their performance limits. In other industries, the wire and cable insulation and shielding materials, both internal and external, must demonstrate heat-resistant properties and enhanced shielding performance [3]. The traditional development of the wire and cable industry is constrained by the necessity to compete on the basis of low prices. This has created an urgent need for new technologies and materials that can reduce costs[4]. Consequently, the development of a new type of cable material is likely to provide a solution to the current difficulties faced by the cable industry, thereby facilitating the growth of the wire and cable industry[5].

In 2004, Geim et al., the professor of physics at the University of Manchester, in UK, exfoliated and observed graphene, a quasi-two-dimensional material of elemental carbon, in a remarkably straightforward manner[6][7]. The distinctive structure of graphene, which exhibits a series of exceptional properties, including a perfect quantum tunneling effect, a half-integer quantum Hall effect, and an unwavering electrical conductivity, has led to the emergence of immense potential in material applications. In typical laboratory settings, monolayer graphene exhibits a multitude of exceptional properties, including electron mobility that is two orders of magnitude higher than that of the widely utilized semiconductor silicon. Additionally, it displays ultra-high thermal conductivity and specific area, along with remarkably high Young's modulus and fracture stress, which render graphene materials potentially invaluable for cable applications. Furthermore, it has been demonstrated that stirred friction processing (FSP) facilitates the efficient mixing of graphene with a metal matrix, resulting in the production of graphene/metal matrix composites with enhanced properties.Liu et al. successfully demonstrated the use of FSP for the in-situ graphite exfoliation to produce bulk graphene composites [8], which eliminates the need for additional processing steps or suppresses the introduction of unwanted impurities, thus allowing for the incorporation of graphene into the metal matrix. This approach provides a potential solution for realizing the desired graphene/metal composites. Aishani Sharma et al. utilized a novel The SolidStir extrusion process (SSE) was employed to achieve in-situ exfoliation of graphite into multilayered graphene. The formation of multilayers of graphene during SSE resulted in a notable enhancement in the strength of aluminum alloys[9], as compared to pure SSE. This notable improvement in strength has the potential to revolutionize the wire and cable industry, offering a valuable opportunity for businesses to develop innovative cable materials.

This paper reviews the research progress of graphene in enhancing the performance of cable materials, beginning with an examination of the unique structure and excellent properties of graphene. It then focuses on the optimization of graphene's performance on copper as a cable conductor material and the improvement of graphene in the application of composite semiconducting inner and outer shielding layers of cables. Additionally, it introduces new applications of graphene cables and explores the prospects for their future application.

2. Optimization of Graphene

2.1 Mechanical Properties

In regard to its mechanical properties, graphene displays remarkable resilience due to the robust C-C bonding energy and its distinctive six-membered ring structure. Lee C. et al. conducted experimental measurements of the mechanical properties of a complete single-layer graphene. [10], and the results demonstrate that its theoretical modulus of elasticity is as high as 1.02 GPa, and its fracture strength is as high as 130 GPa, which is approximately 100 times that of high-strength steel. However, the results of molecular dynamics studies suggest that the strength of graphene may decrease with an increase in graphene layers. Upon attaining 10 layers, the theoretical fracture strength is projected to decline to approximately 80 GPa [11]. Moreover, the unsupported single-layer graphene mechanical properties were assessed through experimental measurements, yielding a tensile strength of 50 Pa to 60 Pa, which is approximately half of the theoretical value [12]. However, the results also demonstrated that the actual conditions of graphene exhibited significantly higher mechanical properties than those of conventional metal materials. The substitution of conventional metals in cable applications can result in a notable enhancement in tensile strength, which is a crucial attribute in aerospace, large transmission lines, and other domains where high-strength cables are essential.

2.2 Electrical Properties

In regard to its electrical properties, graphene's unique chemical structure, comprising conjugated π-bonds, endows each carbon atom with the capacity to facilitate the unrestricted movement of π-electrons within the plane of the graphene sheet. This intrinsic property enables graphene to exhibit an exceptionally high electron mobility, reaching $2×10^5$ $cm^2V^{-1}s^{-1}$, a value that is more than six thousand times greater than that of copper, a traditional conductive material. This value is 6,000 times that of the traditional cable conductor material, copper. Consequently, graphene is the best conductive material at room temperature, with a conductivity of up to 1×106 S/cm, which is 1.7 times higher than that of copper [13]. Moreover, Wonmo Kan and colleagues demonstrated that the synthesis of axially continuous graphene layers on micrometer-diameter wires led to a notable enhancement in electrical properties [14] , with a 450% increase in current density breakdown limit and excellent thermal stability, including a 224% increase in surface heat dissipation after The material demonstrated thermal cycling capabilities up to 450 °C, exhibiting a 41% increase in electrical conductivity, a 41.2% decrease in resistivity, and a 41.2% decrease in electrical resistance. These properties are notable improvements over those of conventional pure copper wires. This results in an increase in current density, electrical conductivity, long-term oxidation resistance at high temperatures, and thermal stability in comparison to conventional pure copper wires. Despite being concluded for products manufactured under laboratory conditions, the aforementioned studies provide new engineering solutions for optimizing the technical limits of cables for the operation of modern power systems for high power transmission, including the aerospace industry, transportation systems, and advanced electronics and communications equipment.

In conclusion, the incorporation of graphene into cable materials markedly enhances electrical conductivity, tensile strength, and resilience against heat-related deterioration and damage. Additionally, it reduces energy consumption and enhances transmission efficiency and service life, thereby revolutionizing advancements in the cable industry.

3 Graphene Applications in Cable Materials

3.1 Copper-based Composites and 3D Graphene-copper Composites

Copper is the most commonly utilized conductor material in wires and cables. With the advancement of the industry, the standards for the performance of copper wires and cables are becoming increasingly rigorous. Current research indicates that conductivity exceeding 100% has been achieved in ICAS copper-based graphene composites manufactured under laboratory conditions.

Cao et al. embedded graphene in metallic copper[15], where graphene overcame the trade-off between carrier mobility and carrier density, achieving both high electron mobility and high electron density through careful interface design and morphology control. Consequently, the electrical conductivity of the bulk graphene/copper composites with a minimal graphene volume fraction (0.008) was found to be approximately 17% of the international standard for annealed copper, exhibiting a notable enhancement in comparison to that of Ag.

Zhang et al. presented a powder metallurgy-based approach to fabricate a three-dimensional continuous graphene network structure within a copper matrix in a recent study[16]. This was achieved through the application of thermal stress-induced welding between graphene-like nanosheets that had been grown on the surface of copper powder. The interpenetrating structural features of the obtained composites elevate the interfacial shear stress to a high level, thus significantly enhancing both load transfer strengthening and crack bridging toughening. Additionally, they construct 3D superchannels for electrical and thermal conductivity. The electrical conductivity of the composites reaches 103.4% IACS.

Yang Jun et al. employed chemical vapor deposition (CVD) to cultivate multilayered graphene films on the inner and outer surfaces of pre-prepared three-dimensional porous copper [17]. The resulting graphene films exhibited near-complete coverage of the copper surface. Subsequently, the porous copper-graphene composite structure was subjected to powder metallurgy-based pressing and sintering, and then extruded into a graphene/copper composite wire with a diameter of 4 mm. A conductivity test revealed that the copper-graphene composite wire exhib-

ISSN 2959-6157

ited a conductivity of 101.0% IACS, which surpassed the international standard for annealed copper. Furthermore, the general conductivity exceeded the international standard for annealed copper. Materials comprising copper are designated as ultra-high conductive copper materials. Furthermore, the high-temperature load capacity of the composite wire was evaluated using a cable load burning test machine, demonstrating an increase of 5.45% compared to pure copper wire. The electrical conductivity and current-carrying capacity of the composite materials exhibited superior performance compared to pure copper.

In addition, some researchers have also fabricated 3D graphene-copper composite wire and cable under laboratory conditions [18]. The use of three-dimensional graphene three-dimensional skeleton structure, and then through the subsequent and copper powder vacuum hot pressing sintering, drawing, and then repeatedly annealed and stretched, the outer insulation layer and other processing procedures, in which the graphene is connected to the three-dimensional mesh structure, the stability of the graphene framework to ensure its continuity in the copper, and the performance of the linear performance of the pure copper compared to the conductivity and copper close to the conductivity of the conductor, but the flow rate of the current-carrying capacity is higher than that of the pure copper 1.5-2.4 times, and the hardness is significantly better than pure copper. And the hardness is significantly better than pure copper, retaining its conductivity in good condition, improve the mechanical strength and flow-carrying capacity, so that the composite material has excellent electrical conductivity and high flow-carrying capacity.

This strategy is straightforward, requires minimal preparation time, and has broad applicability. However, the method has potential limitations. While the preparation process of porous copper-graphene composite structures is described in detail, the discussion of copper-graphene composite wires is more speculative and qualitative, lacking a substantial number of extensive data points to support its claims. The dimensional graphene-copper composite wires and cables that have been produced thus far are limited to a small number of experimental samples, and their application in industry is not yet widespread. Consequently, further in-depth study is required in order to meet the demands of the wider production sector.

3.2 Improvement of Graphene for the Application of Composite Semiconductive Inner and Outer Shielding layer

As a crucial component of the high-voltage DC cable structure, the semi-conductive shielding layer (referred to as the “semi-conductive layer”) plays a pivotal role in homogenizing the electric field distribution within the insulating material, whose structure is shown in Figure 1. The insulating layer eliminates the air gap between the conductor core and the insulating layer, as well as the interface between the insulating layer and the outer conductive layer. This prevents partial discharges and increases the stability of cable operation and service life. However, as the operational lifespan of high-voltage DC cables increases, the accumulation of internal space charges becomes increasingly significant. This phenomenon negatively impacts the electrical performance of the insulating material, potentially jeopardizing the safe and stable operation of the cable [19].

The experimental results presented by Guochang Li and colleagues [20] demonstrate that a composite high-semiconducting conductor shielding material, comprising an appropriate amount of graphene in place of the traditional semiconducting layer shielding material, carbon black, can effectively reduce the accumulation of charge in the insulating layer. Furthermore, it can improve the cable’s performance in the case of an uneven electric field, thus avoiding potential issues. The occurrence of localized discharges in the conductor and the insulating layer between the conductor and the insulating layer is simultaneously reduced, thereby reducing the incidence of abnormal cable operation processes, such as cracking. Furthermore, power loss and electromagnetic radiation pollution are diminished, while the external electromagnetic environment’s interference with the cable signal is effectively prevented. This ensures the quality of transmission and enhances electromagnetic compatibility.

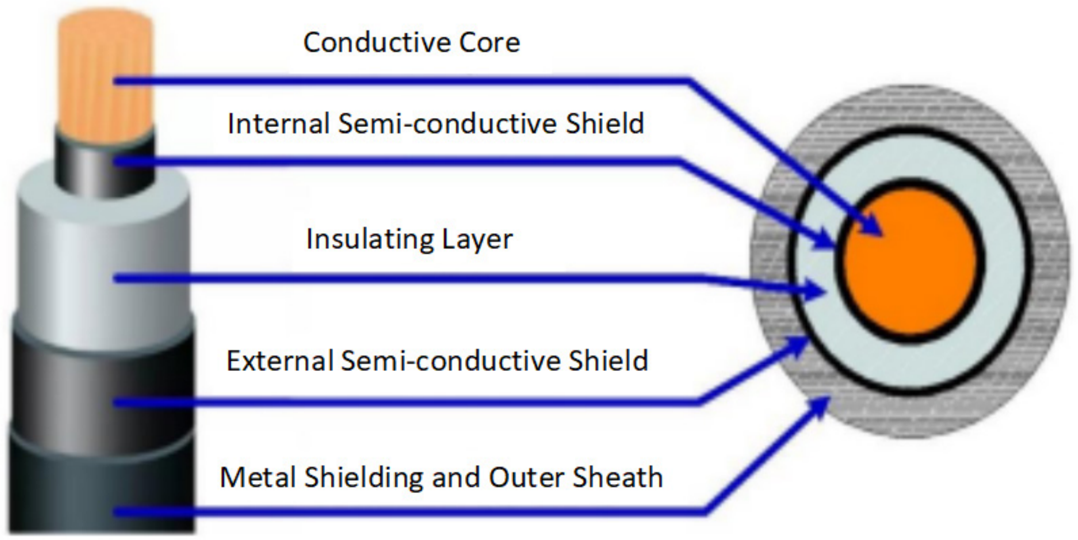

Fig.1 Schematic representation of the structural configuration of a high-voltage direct current (DC) cable.

Moreover, researchers have developed a novel graphene composite, comprising high-semiconducting internal and external shielding, impact-resistant power cable (Figure 2). In comparison to traditional cables manufactured with semiconducting shielding materials, the incorporation of graphene shielding materials in the shielding layer not only enhances the conductivity and shielding efficiency of the shielding material but also improves its extrusion performance. The extruded shielding layer is rendered smoother, thereby reducing the generation of partial discharges. Furthermore, the electric field around the cable becomes more uniform, which in turn enhances the reliability and safety of cable operation and prolongs its operating life.

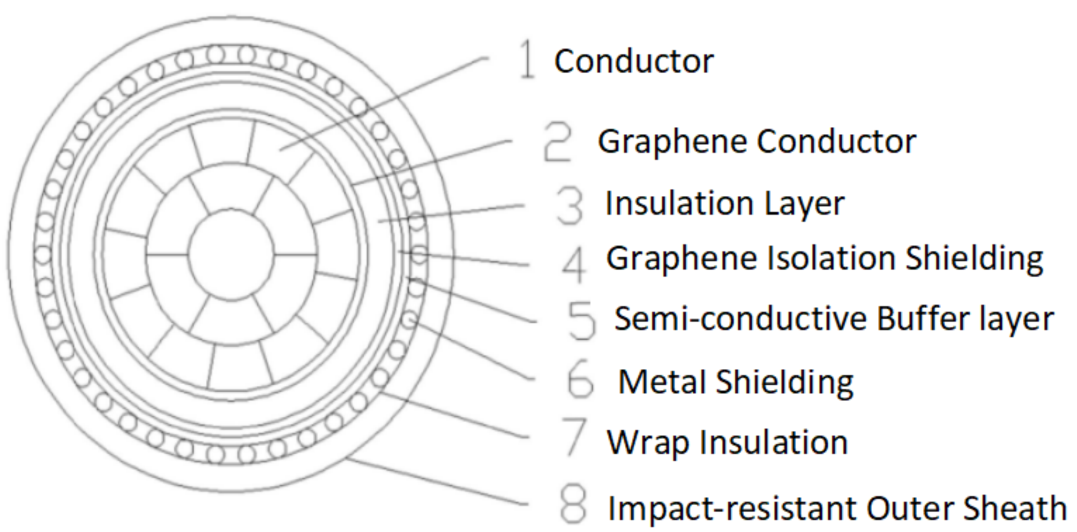

Fig.2 Schematic structure of graphene composite high semiconducting internally and externally shielded impact resistant power cable[21]

3.3 Additional Forms of Graphene Cables

3.3.1 Nano-Coated graphene cables

Derivative new products of wire and cable are primarily the result of the adoption of new materials, special materials, or alterations to the product structure, improvements to the process requirements, or the combination of different varieties of products due to varying application occasions, application requirements, and the requirements of convenience of equipment and reduction of equipment costs. In certain work environments, it may be necessary to enhance the conductivity of the cable in order to facil-

ISSN 2959-6157

itate optimal functionality. In such instances, the typical cable components tend to be relatively fixed, making it challenging to augment other components through increased conductivity. Consequently, the internal conductor of the cable must be optimized to fulfill its intended role of enhancing conductivity.

Researchers have developed a graphene nano-coated cable with enhanced conductivity through the optimization of the core conductor components and the addition of a nano-graphene layer to match the laminated shielding line structure[22], which is composed of the cable core. The structure of this cable is illustrated in Figure 3. This allows for an effective improvement in the conductor's own conductivity efficiency, as well as the utilisation of the outer layer of the shielding component to guarantee the cable's transmission efficacy. This approach helps to circumvent the potential influence of external factors that could otherwise impact the operational effectiveness. Ultimately, this enables a comprehensive enhancement in the overall conductivity.

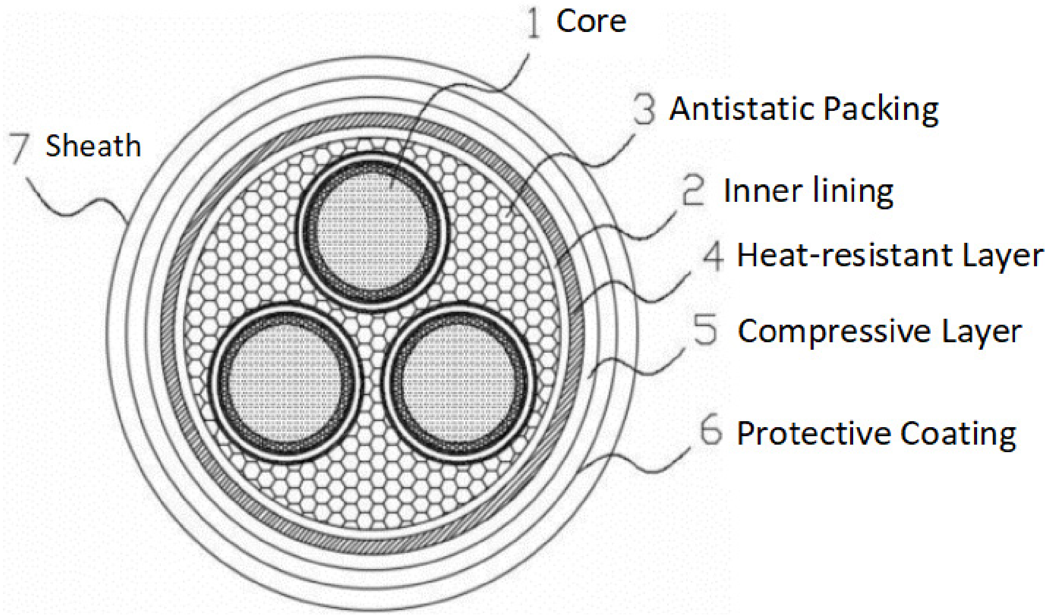

Fig.3a Schematic of graphene nano-coated cable structure[22]

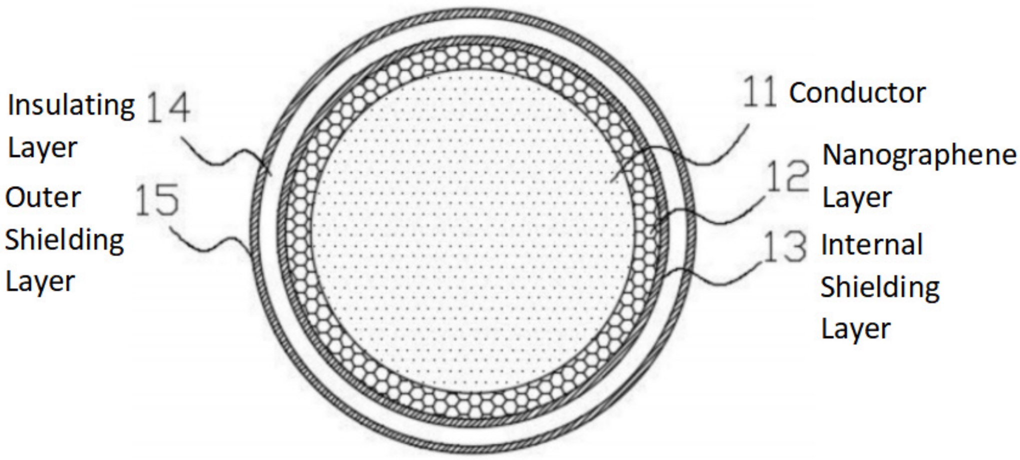

Fig.3b Schematic structure of graphene nano-coated cable conductor section[22]

3.3.2 Graphene-Insulated composite cable

The structure of the graphene-insulated composite cable is illustrated in Figure 4. It comprises a core unit, a shielding layer, and a protective layer from the innermost to outermost components. The core is composed of a conductor, an insulating layer, and a graphene semiconducting layer from the innermost to outermost components. The preparation process is compact and consistent, which is conducive to the continuous and efficient production of the cable.

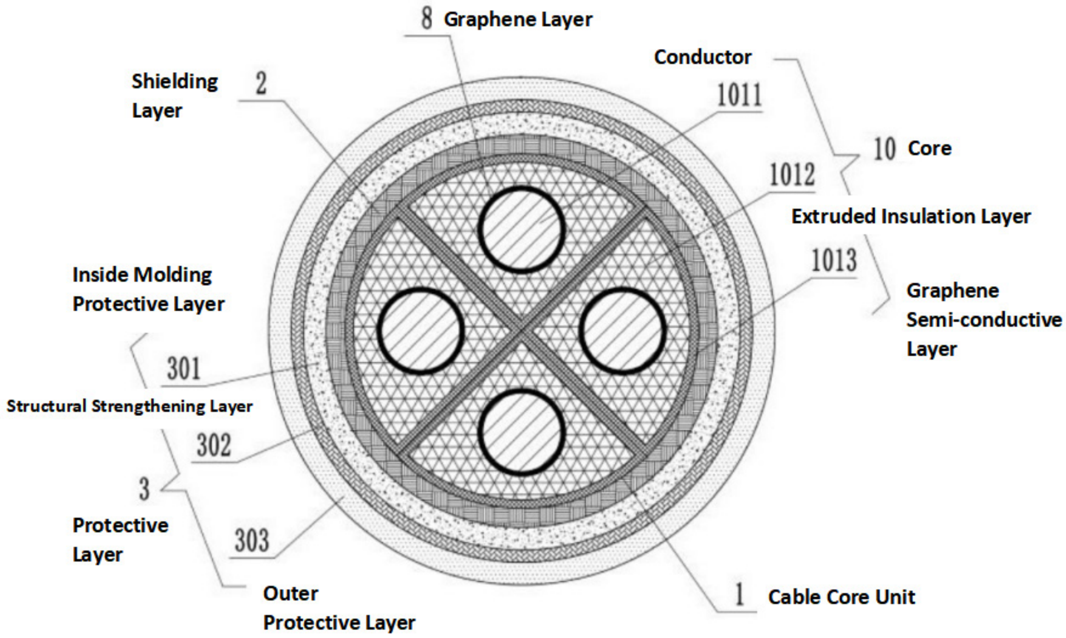

Fig.4 Schematic structure of graphene insulated composite cable[23]

In comparison with the conventional cable, the improved effect of this graphene-insulated composite cable is as follows[23]:

(1)Compared to the prior art in which there is a gap between a plurality of cable cores when they are formed into a cable, resulting in noise that is easily generated during use due to relative displacement between conductors and between other components. By changing the contact method between adjacent cable cores, the existing cylindrical fitting is changed to face contact so that the plurality of cable cores can maintain a stable relative position without setting filler materials, thereby reducing the relative displacement between cable cores due to external forces in the use process and effectively reducing noise.

(2)The semi-conductive layer is made of graphene, which can effectively improve the strength of the cable, and the graphene semi-conductive layer has good electrical conductivity and smoothness, which can effectively prevent the generation of electrical charges and discharges, further reducing noise.

(3)Compared with the prior art, in order to reduce the noise and filler materials set up to cause the cable preparation efficiency of the process, in the molding of the cable core can be obtained directly adjacent to the core for the face contact of the core structure, so that in the subsequent formation of the cable between the different cores do not need to set up filler materials can be stably linked together, avoiding the existence of the central gap, reduce the existing filler materials of the process steps, and effectively improve the efficiency of cable preparation.

4 Application Prospects of Graphene Cables

The market application prospects of graphene cables include high-voltage, ultra-high-voltage and extra-high-voltage power transmission, as well as electric vehicles, high-speed railways and other railway transportation fields. In addition, the excellent corrosion resistance and mechanical properties of graphene cables make them suitable for use in fields such as marine engineering and petrochemicals. Technological innovation and cost reduction will further promote the application of graphene in cable materials, and it is expected that graphene cables will occupy an important position in the marine engineering and petrochemical markets in the future.

The application of graphene cable in the field of marine engineering is mainly focused on improving the corrosion resistance and durability of the cable. The marine environment is harsh and contains salt and microorganisms, all of which accelerate the ageing and damage of conventional cable materials. Graphene coating technology can be applied to the anti-corrosion protection of ships, offshore platforms and other marine engineering structures, effectively preventing seawater corrosion, extending the life of the structure and improving the safety of marine engineering.

In the context of the petrochemical industry, graphene

ISSN 2959-6157

cables can be employed for the purpose of anti-corrosion protection of oil drilling platforms, oil pipelines and other relevant equipment. The chemical stability and corrosion resistance of graphene enable it to resist the erosion of a variety of corrosive media, including acids, alkalis, salts and organic solvents. This property extends the service life of the equipment.

The potential for graphene cables has also been the subject of market analysis, with major industry players initiating research and development, production, and commercialisation activities. These developments have been accompanied by a gradual promotion and exploration of the commercial applications of graphene in the field of cables. To illustrate, the graphene cable products of Zhongchao Holdings have reached the stage of industrial production and are supplied in bulk to cable manufacturing enterprises in several provinces and cities [24]. Furthermore, the graphene cable project developed by Hangdian and the University of New South Wales, Australia, has also made progress, and the graphene cable samples are undergoing official testing and are planned to be demonstrated for industrialisation [25].

As graphene research progresses and production costs decline, it is anticipated that its utilisation in the electrical sector will become more prevalent, with a significant role anticipated in the future energy transmission and high-performance cable industries.

5 Conclusion

The excellent comprehensive properties of graphene have already led to its use in a number of applications within the field of cables. Recently, research has been conducted into the preparation of graphene cables for a variety of applications, with different methods being employed in order to achieve the desired outcome.

The synthesis of a composite material comprising graphene in a laboratory setting has enabled the production of a conductor with a conductivity exceeding 100% ICAS, representing an ultra-high conductivity level for copper materials. Furthermore, the creation of a three-dimensional graphene composite conductor in copper has resulted in the development of a highly conductive and high-current-carrying wire and cable, effectively surpassing the performance limitations of traditional copper cable conductors. The incorporation of graphene into cable composites has facilitated the introduction of a semiconducting layer on the inner and outer surfaces of the shielding layer, enhancing the insulation properties of the insulated core and imparting a smoother appearance. The utilisation of graphene in cable composites serves to diminish the occurrence of localised discharges, whilst simultaneously fostering a more uniform electric field surrounding the cable. This, in turn, enhances the reliability and safety of cable operation. Furthermore, the graphene nano-coated cable exhibits high conductivity, effectively combating material erosion. The preparation process is straightforward and cost-effective, rendering it suitable for large-scale production. The insulated composite cables, which incorporate graphene, are designed with the objective of enhancing the insulating properties of cables and reducing noise. Additionally, they seek to mitigate the occurrence of partial discharges, which may arise during the operation of cables, and to extend the service life of the cable.

The aforementioned application cases illustrate that the utilisation of graphene in the domain of cables is not merely a conventional single or multifaceted innovation. Rather, it is an endeavour that seeks to address the inherent limitations of conventional cable materials and enhance their performance, thereby paving the way for the advent of a new generation of high-performance cables. With continued research and the industrialisation of graphene, it is anticipated that graphene will become a more pervasive element within the cable industry.

China is currently the leading nation in global research and industrialisation in the field of graphene. The combined efforts of the government and private enterprises have accelerated the industrialisation of graphene cables, resulting in notable advancements. However, the application of graphene in the field of cables still presents certain challenges, including the need to enhance the stability and reduce the cost of graphene materials, as well as to perfect the related production process and standardisation. It is anticipated that, as the technology continues to mature and market demand grows, graphene will play an increasingly important role in the future power transmission system.

References

[1] China Industry Research Institute. Wire and Cable Market Market Sentiment Analysis and Related Technology In-depth Research Report, 2024-2029 Edition.2024.

[2] Sihan Industrial Research Institute. Competitive Pattern of Wire and Cable Industry at Home and Abroad.2024-04-01. Competitive Pattern of Wire and Cable Industry at Home and Abroad-Industry News- Industry News- Sihan Industrial Research Institute (chinasihan.com).

[3] B Li,F Li,Q Fan, et al. Progress of Graphene Application in Cable Materials. Aircraft Design,2020,40(01):21-26.

[4] Bolotin K I, Sikes K J, Jiang Z, et al. Ultrahigh electron mobility in suspended graphene. Solid State Communications, 2008, 146(9): 351-355.

[5] Basko D M. Boundary problems for Dirac electrons and

edge-assisted Raman scattering in graphene. Physical Review B, 2009, 79(20): 205428-205449.

[6] Akhmerov A R, Beenakker C W J. Boundary conditions for Dirac fermions on a terminated honeycomb lattice. Physical Review B, 2008, 77(8): 085423.

[7] Huijie Zhang, Baoxin Zhang, Qiuzhi Gao, Jianling Song, Guoliang Han,A review on microstructures and properties of graphene-reinforced aluminum matrix composites fabricated by friction stir processing, Journal of Manufacturing Processes,2021, 68: 126-135.

[8] Yijun Liu, Gaoqiang Chen, Hua Zhang, Chengle Yang, Shuai Zhang, Qu Liu, Mengran Zhou, Qingyu Shi,In situ exfoliation of graphite for fabrication of graphene/aluminum composites by friction stir processing,Materials Letters ,2021.

[9] Aishani Sharma, Ravi Sankar Haridas, Priyanka Agrawal, Anurag Gumaste, Thomas Scharf Kumar Kandasamy, Rajiv S. Mishra,Novel SolidStir extrusion technology for enhanced conductivity cable manufacturing via in-situ exfoliation of graphite to graphene,Materials Design,2024.

[10] LEE C,WEI X,KYSAR J W,et al.Measurement of the elastic properties and intrinsic strength of monolayer graphene. Science,2008,321(5887):385-388.

[11] Zhong Teng. Molecular dynamics study of mechanical properties of multilayer graphene. Xiangtan: Xiangtan University,2019.

[12] CAO K,FENG S,HAN Y,et al.Elastic straining of free-standing monolayer graphene.Nature Communications, 2020,11:284.

[13] GEIM A K,NOVOSELOV K S,The rise of graphene.Nature Materials,2007,6:183-191.

[14] H. Kashani, C. Kim, C. Rudolf, F. K. Perkins, E. R. Cleveland, W. Kang, An Axially Continuous Graphene–Copper Wire for High-Power Transmission: Thermoelectrical Characterization and Mechanisms.Adv. Mater. 2021, 33: 2104208.

[15] Cao, Mu; Xiong, Ding-Bang; Yang, Li; Li, Shuaishuai; Xie, Yiqun; Guo, Qiang; Li, Zhiqiang; Adams, Horst; Gu, Jiajun; Fan, Tongxiang; Zhang, Xiaohui; Zhang, Di. Ultrahigh Electrical Conductivity of Graphene Embedded in Metals. Advanced Functional Materials, 2019.

[16] Zhang, X., Xu, Y., Wang, M. et al. A powder-metallurgy-based strategy toward three-dimensional graphene-like network for reinforcing copper matrix composites. Nat Commun, 2020.

[17] Jun Yang,Yu Ma,Jinliang Fu.CVD synthesis of three-dimensional graphene-copper composites and their ultrahigh conductivity. Materials Herald,2024,38(S1):372-378.

[18] State Intellectual Property Office of the People's Republic of China -Patent application for invention- "Preparation method of three-dimensional graphene-copper composites and composite wires and cables" - CN 109295333 A-2019.02.01

[19] Li Xuejing. Effect of graphene-modified semiconducting shielding on the charge accumulation characteristics of high-voltage cable insulation layer. Qingdao University of Science and Technology,2022.

[20] Li, G., et al.: Effect of graphene modified semi-conductive shielding layer on space charge accumulation in insulation layer for high-voltage direct current cable.High Volt, 2022, 7(3):545–552.

[21] State Intellectual Property Office - Patent Application for Invention -"A kind of Graphene Composite High Semi-Conductivity Inner and Outer Shielded Shock-Resistant Medium Voltage Power Cable" -CN 116779239 A-2023.09.19

[22] State Intellectual Property Office - Utility Model Patent - "A kind of conductivity increasing graphene nano-coated cable" - CN 218274032 U-2023.01.10

[23] State Intellectual Property Office - Patent Application for Invention -"A Graphene Insulated Composite Cable and Its Preparation Method" - CN 117612776 A-2024.02.27

[24] ChinaDaily.com.cn 2021.3.12 "Carbon-neutral industry catches wind, graphene cable producer Zhongchao Holding gets attention" Carbon-neutral industry catches wind Graphene cable producer Zhongchao Holding gets attention - chinadaily.com.cn

[25] Graphene.com:September 6, 2016 "China-Australia cooperative graphene project officially launched http://www.graphene.tv/2016090614699/August 8, 2018 "Graphene cable project developed by Hangdian and Australian universities achieves stage-by-stage results http://www.graphene.tv/201808083927/